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COMPARISON OF GAIT MECHANICS AND FORCE GENERATION DURING UPRIGHT TREADMILL AND SUPINE LBNP EXERCISE.

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Introduction

One of the goals of space exploration is a manned flight to Mars. However, many physiological decrements occur during long space flights such as losses in muscle strength, bone density, balance, and aerobic capacity which would make a long duration space flight unfeasible. Therefore, devices must be developed which will reduce or eliminate these byproducts of space flight. One strategy is to have astronauts exercise during space flight. Many exercises on earth, particularly walking and running have been shown to improve muscle strength, bone density and aerobic capacity.

Recently a device has been developed for zero-gravity exercise, a LBNP (Lower Body Negative Pressure) chamber. The LBNP device is a chamber which simulates gravity by creating a negative pressure gradient in a chamber. Footward forces can be increased or decreased by altering the negative pressure within the chamber. Subjects lie supine within the chamber with their legs suspended from one another via cuffs, bungee cords, and pulleys, such that each leg acts as a counterweight to the other leg during the gait cycle. The subjects then walk or run on a treadmill which is suspended vertically within the chamber. This avoids the effects of gravity on the footward forces but allows footward force production due to the negative pressure within the chamber.

Motion studies in this LBNP chamber are one method of analyzing gait in a simulated 1g environment. The purpose of this study was to determine if walking and slow running mechanics are similar on a horizontal treadmill and on a vertical treadmill within a LBNP chamber to simulate gravity for space flight.

Methods

Eight healthy subjects were filmed while walking and running at self selected speeds and at treadmill grades of +4 (uphill), 0 (level) and -4% (downhill) during both upright and supine LBNP conditions. Subjects had a mean age, height and weight of 30.38 years(±1.48), 169 cm (±2.77), and 67.76 kg(±4.40) respectively. Subjects were videotaped at 60 fps using a Minolta C-570 camcorder to obtain five strides of a left sagittal view. The data were digitized using a Peak Performance motion analysis system.
Force data were collected for the x, y and z axes using an AMTI force plate at a sampling rate of 1000 Hz.

Results

Maximum rise distance of the foot was significantly higher during upright running(0.10 ± .004 m) than running in the LBNP chamber (0.08 ± 0.006 m, $p < 0.05$) particularly in the level and upright conditions (see graph 1). Step frequency was faster for running in the LBNP (1.34 ± 0.02 Hz) than upright running (1.29 ± 0.02 Hz, $p < 0.05$) and slower for walking in the LBNP(.87 ± .08) than walking upright.(.91 ± .05 $p < 0.05$), see graph 2). Stance time was longer in the LBNP (0.55 ± 0.03 sec) than upright gait (0.53 ± 0.03 sec, $p<.05$, see graph 3). Knee and hip flexion during swing phase were less in LBNP (67.61 ± 1.71° and 25.24 ± 0.66°, respectively) than upright gait (79.17 ± 1.67° and 28.38 ± 1.03°, respectively; $p < 0.05$, see graph 4 and 5). Knee flexion during stance phase was also less during walking and running in the LBNP chamber (35.83 ± 8.24°) than level walking and running (39.81 ± 8.33°, $p < 0.05$).

Footward forces integrated over each stride were not significantly different between LBNP and upright exercise (see graph 6). Peak forces (push-off) were significantly less in the LBNP chamber (303.16 ± 75.26) than during upright running (254.87 ± 63.91 lbs, $p< 0.05$)(with little variation between uphill, level and downhill conditions, see graph 7). Uphill upright walking is characterized by a larger peak push off force than a landing force. Level upright walking is characterized by equal push off and landing forces and down hill upright walking has larger landing forces and push off forces. These characteristics were not seen in LBNP walking. LBNP walking was always characterized by a larger landing force than push off force. The peak push off force in LBNP was significantly less than the peak push off force occurring during upright walking for uphill, level and downhill walking (see graph 8). The rate of force development was slowest in uphill gait and faster for horizontal gait and fastest for uphill gait. LBNP gait showed a similar rate of force development for the uphill and downhill conditions and a slower rate of force development for the horizontal conditions (see graph 9).

Discussion

Much of the reduced range of motion observed during LBNP exercise is probably due to the leg suspension system and the waist seal in the LBNP. It was also observed that there was no flight phase during the LBNP running condition. Subjects reported that the waist seal held their feet toward the treadmill during what would have been the airborne phase of upright running. This may have been the cause of the increased stance time during the LBNP gait conditions. Therefore running in the LBNP chamber was more similar to race walking than running.

The decrease in knee flexion, hip flexion and maximum rise of the foot during the swing phase of gait is likely due to the leg suspension system in the LBNP. The bungee cords and the back support which extends below the hips, might decrease the overall hip flexion and extension during gait. As the leg extends through the push off phase, there is resistance against the bungee cords at the thigh and ankle holding up the leg. At the most flexed position of gait there is the most resistance from the bungee cord system. At maximum knee flexion and foot rise it is easier for the subject to limit knee flexion than to exert force against the bungee cords.

Why uphill and downhill running do not produce similar force profiles in upright versus supine LBNP gait is not entirely clear.

The footward forces are produced by creating a negative pressure in the LBNP chamber. Without a waist seal the force created by the pressure would be equal on all of the interior surfaces of the chamber. The presence of a waist seal creates a force vector through the subject directed towards the treadmill. During upright gait, gravity exerts a force downward which results in larger impact forces and faster force generation during downhill gait as compared to uphill gait. Because the individual has room to fall downward during downhill gait, the individual has more potential energy during the swing phase of each step. The kinetic energy that results from falling some distance is added to the body weight creating a larger impact force and faster force generation during downhill gait than either level or uphill gait. This is also the reason there is reduced energy expenditure during downhill walking, gravity it pulling the person downward which aids the forward step. During uphill gait an individual must lift his body weight against gravity and impact forces are generally less than level walking. This is also a more expensive condition from a metabolic standpoint because body weight is being lifted through space.

These differences were not seen during LBNP gait; uphill and downhill gait produced similar force profiles in LBNP, which is not the case during upright gait. There are a number of possible reasons for these differences. It is possible that due to the back support, subjects were able to merely change their hip angle slightly to accommodate the change in treadmill angle. It is also possible that the back support holds the person in place rather than letting them fall backward as they would when walking uphill on a treadmill in an upright condition.

In other words, the rebound force from the treadmill would push them backward, but it then changes direction due to the back support which keeps them from falling backward. It is also possible that the force vector resulting from the waist seal and negative pressure is the same at all treadmill angles. The LBNP chamber needs to be tested in a simulated or true zero gravity environment so that subjects can exercise in the chamber without the bungee cords and back support. This type of test should help clarify the findings from this study.

On the other hand the forces produced within the LBNP are well within the ranges needed to produce bone growth. The exercise within LBNP is also physically demanding. Therefore despite the differences in some of the gait mechanics and force profiles the LBNP should be very suitable for exercise in space.

Conclusions

Force generation during gait is a known factor for maintaining bone density in 1G. Observed kinematic and force differences between LBNP and upright treadmill exercise are likely due to the leg suspension system and horizontal orientation of the subject, and would thus be eliminated during space flight. These results support further development of LBNP exercise to simulate 1G exercise in microgravity.

Acknowledgments

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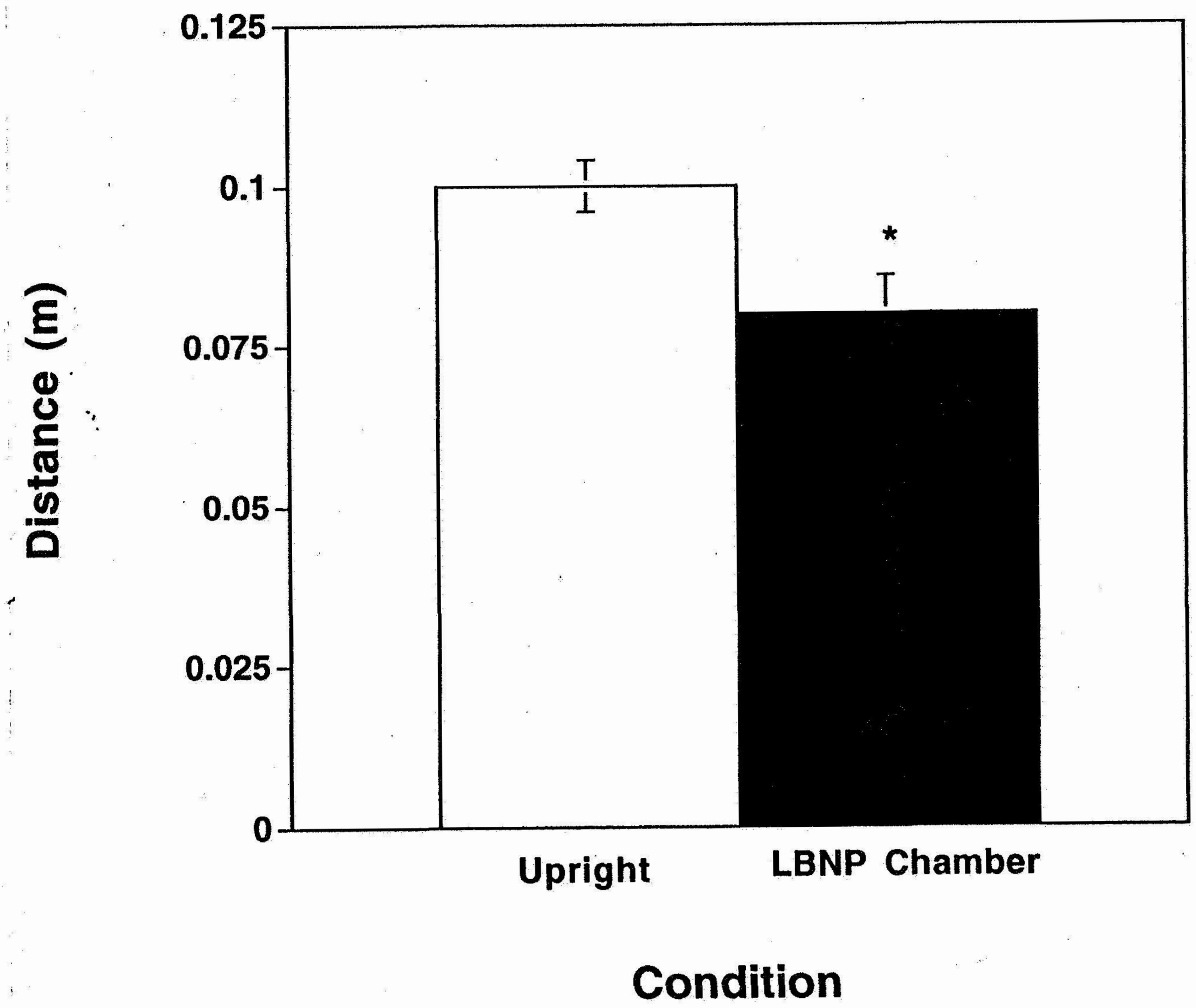
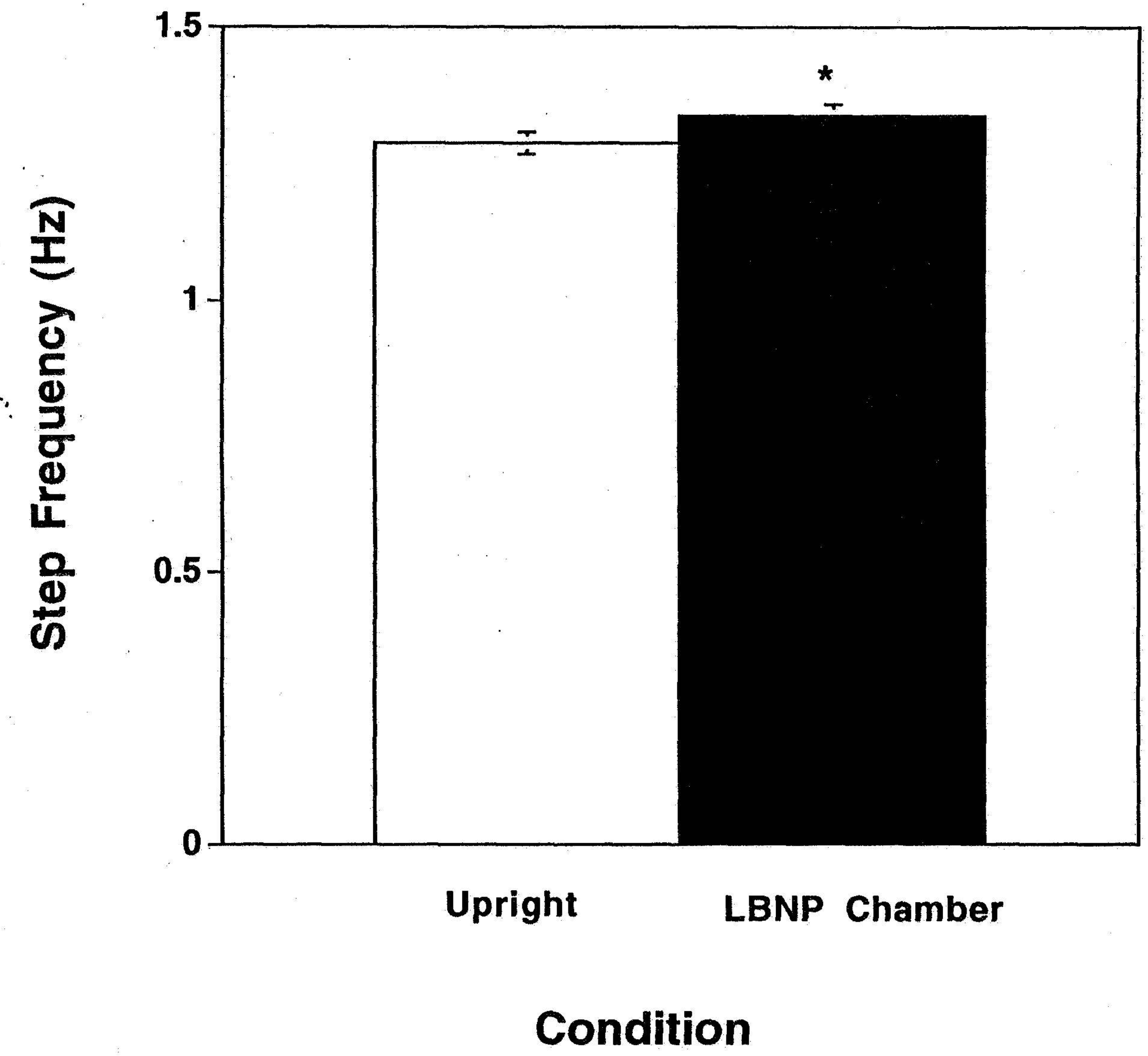
Maximum Rise Distance of the Foot During Upright and LBNPTreadmill Exericse



Step Frequency During Upright and LBNP Treadmill Exercise



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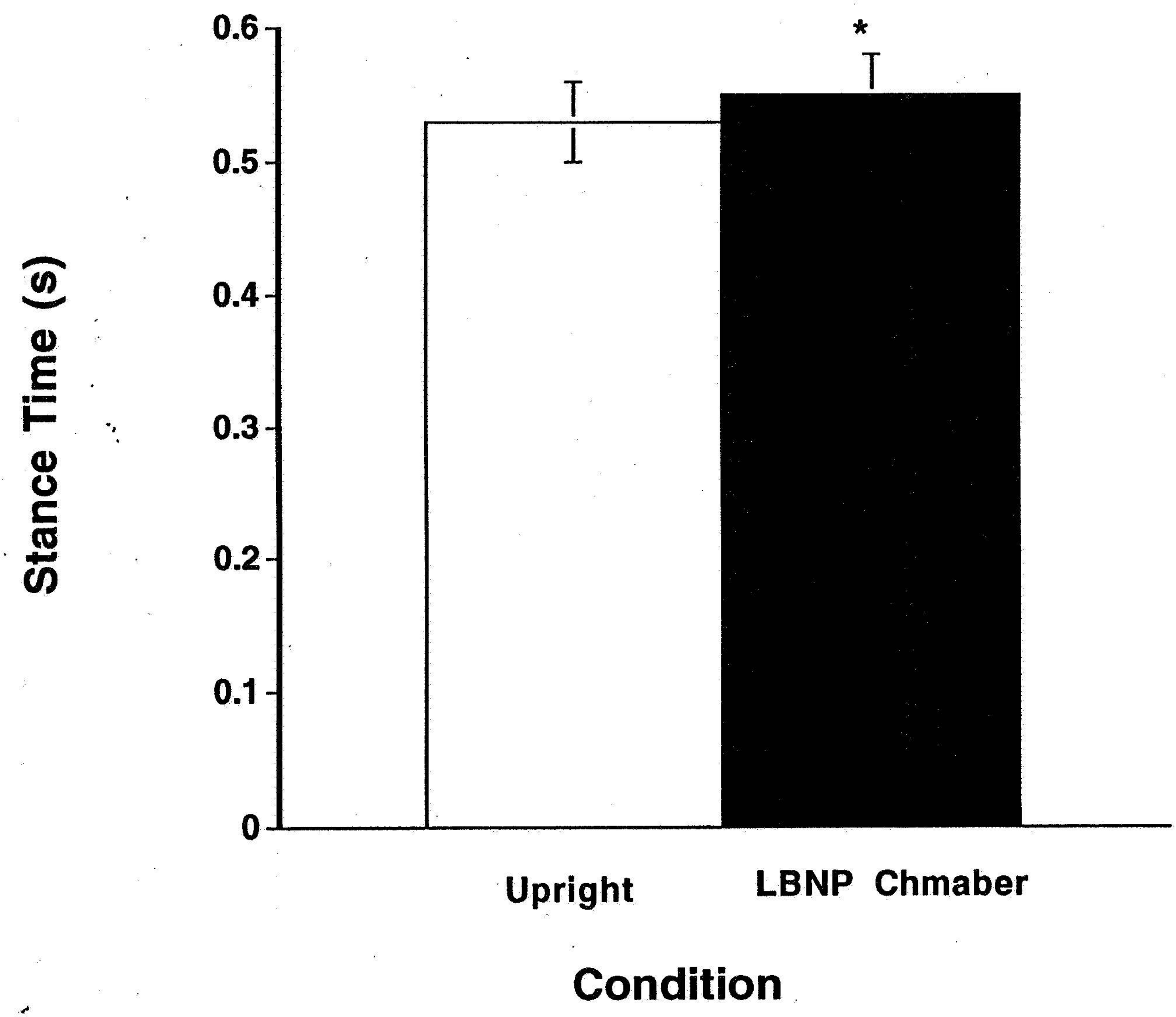
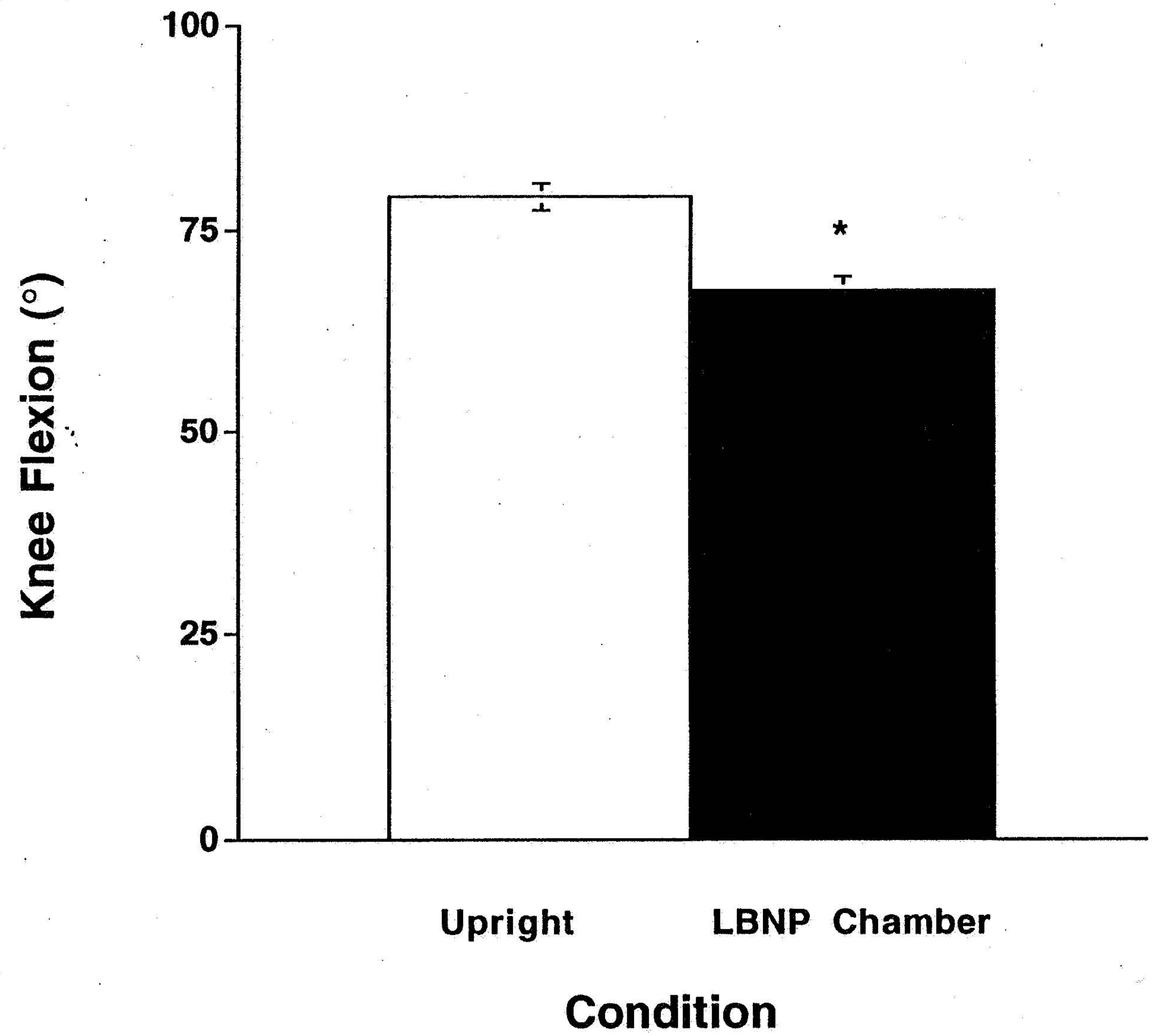
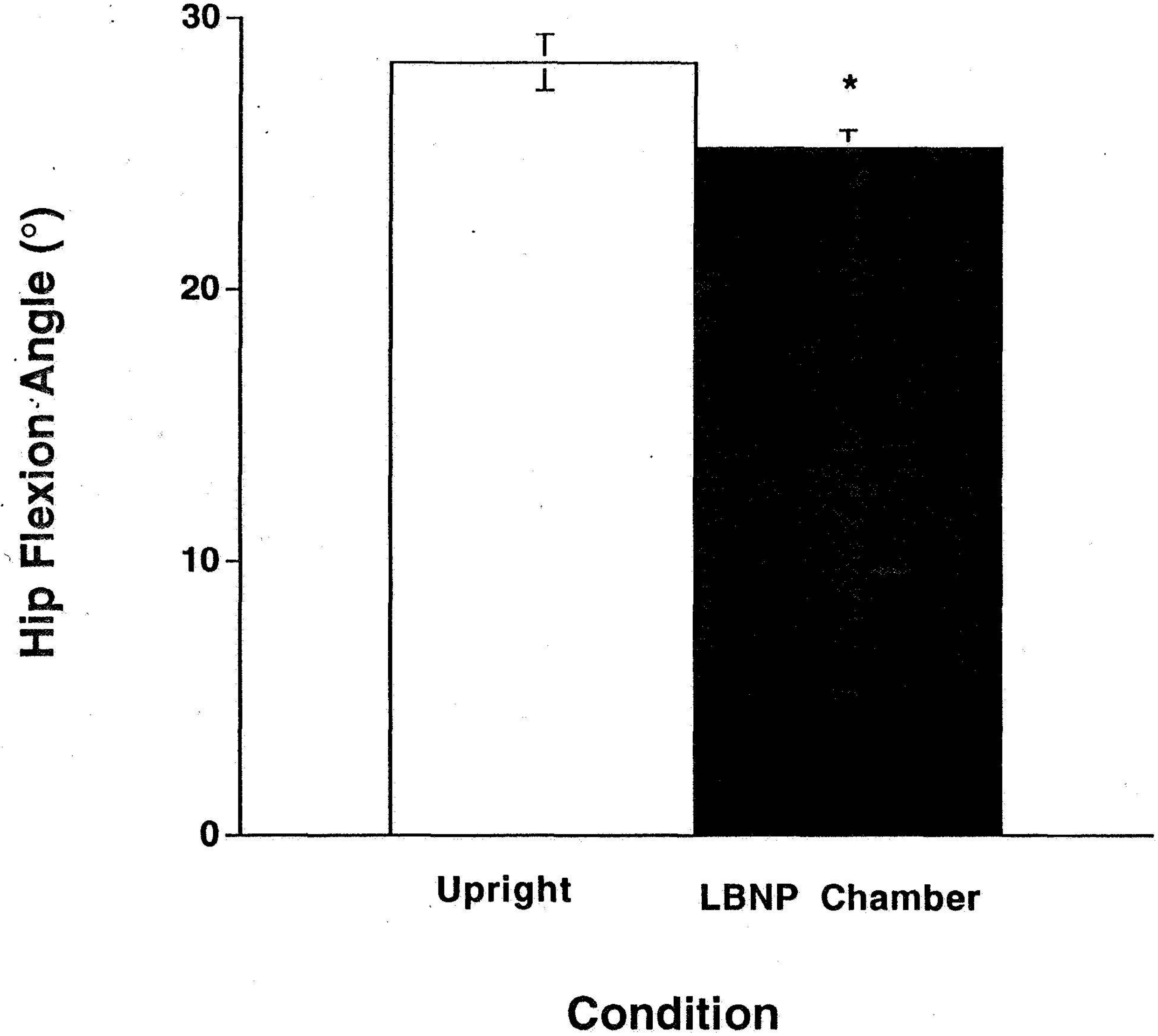
Stance Time during Upright and LBNP Treadmill Exercise

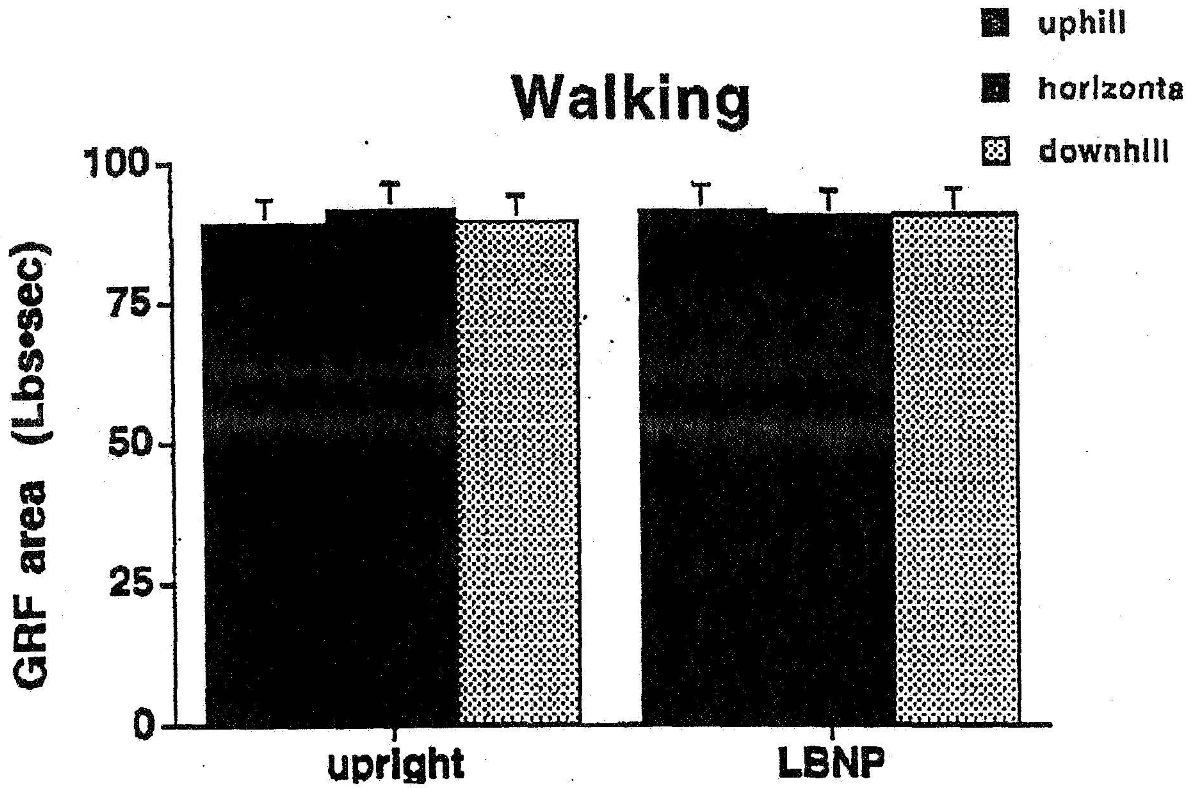


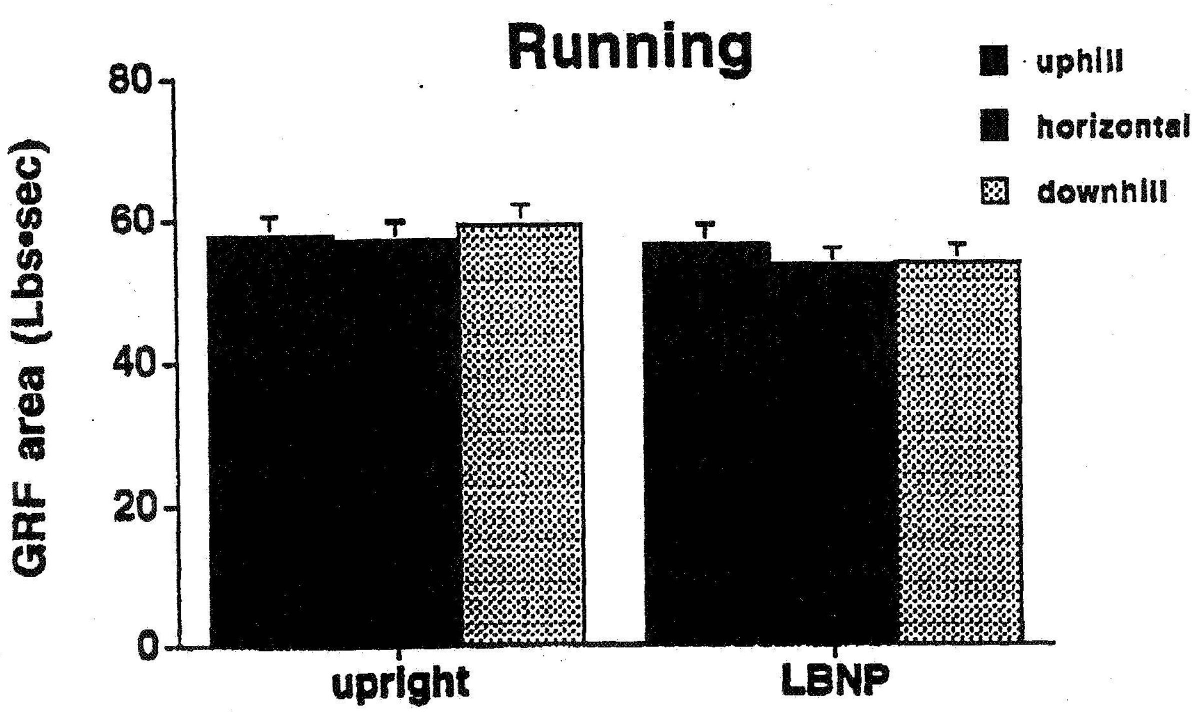
Knee Flexion Angle during Upright and LBNP Treadmill Exercise



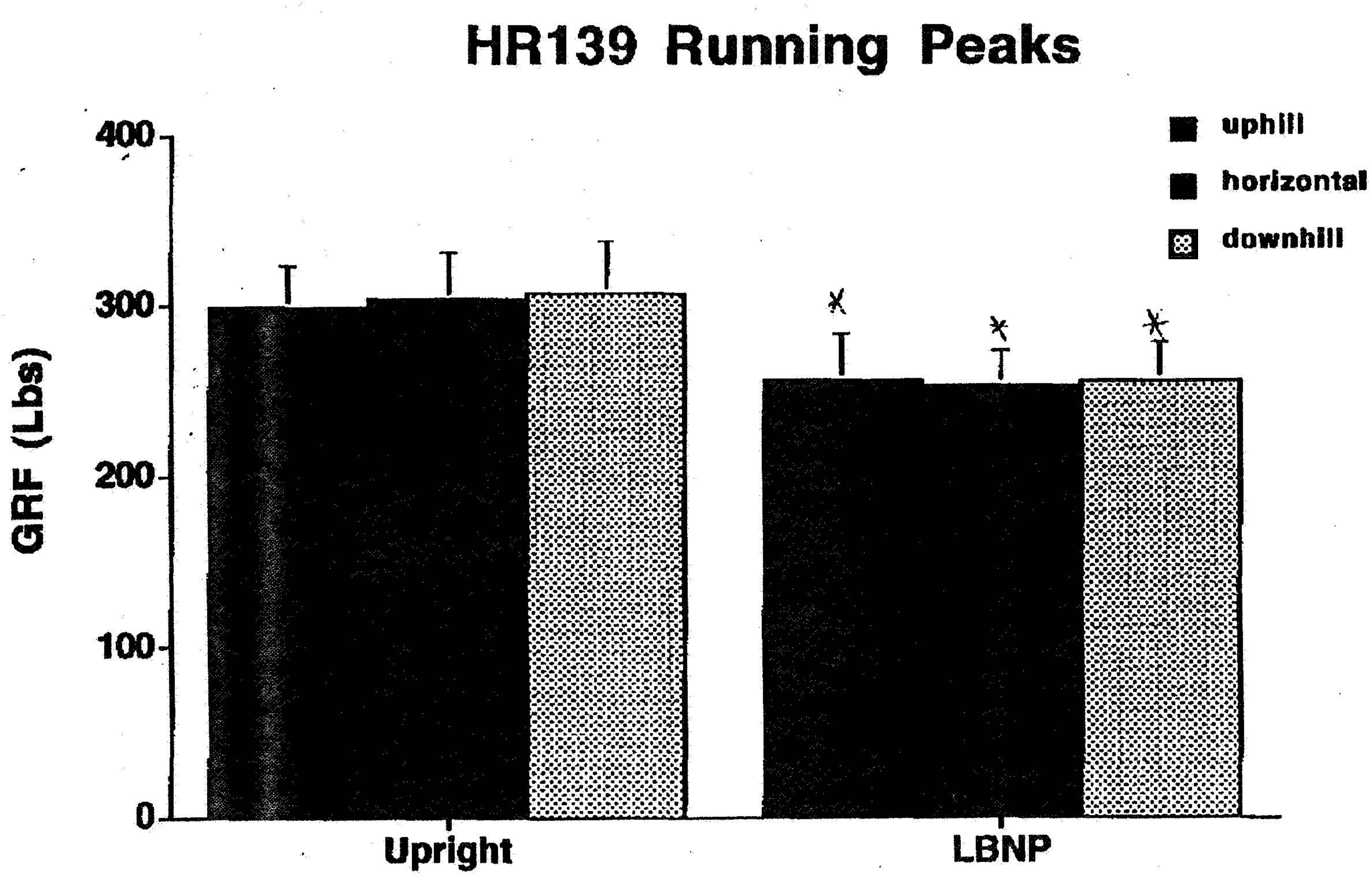
Hip Flexion during Upright and LBNP Treadmill Exercise



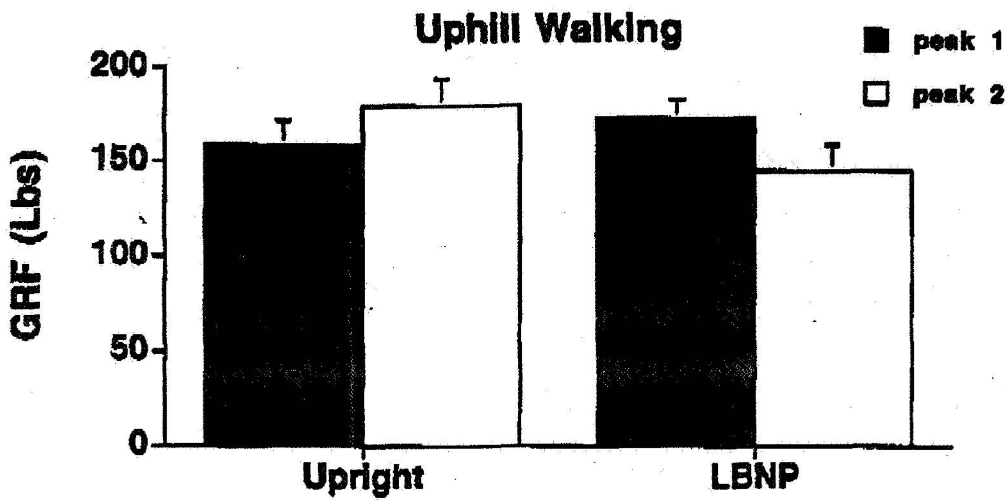

Walking
uphill
horizontal
downhill
GRF area (Lbs•sec)
100
75
50
25
0
upright
LBNP

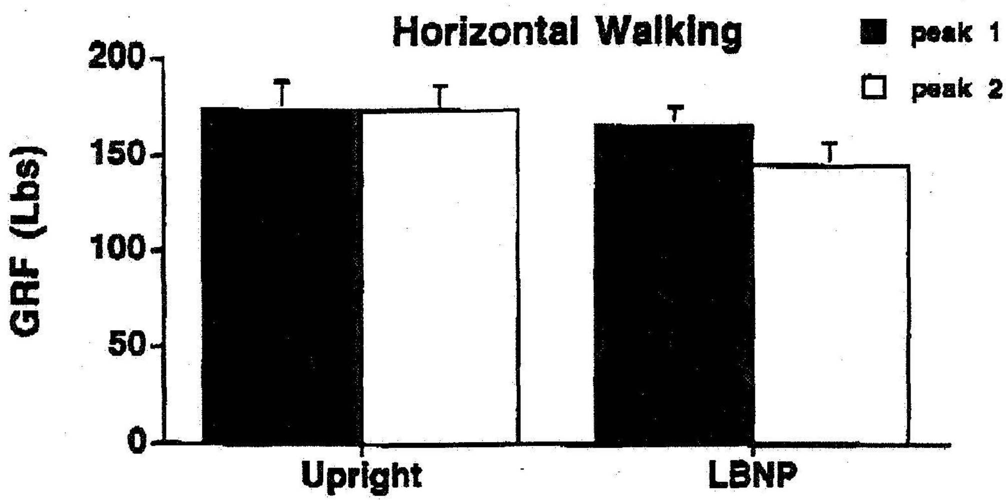

Running
uphill
horizontal
downhill
GRF area (Lbs•sec)
80
60
40
20
0
upright
LBNP

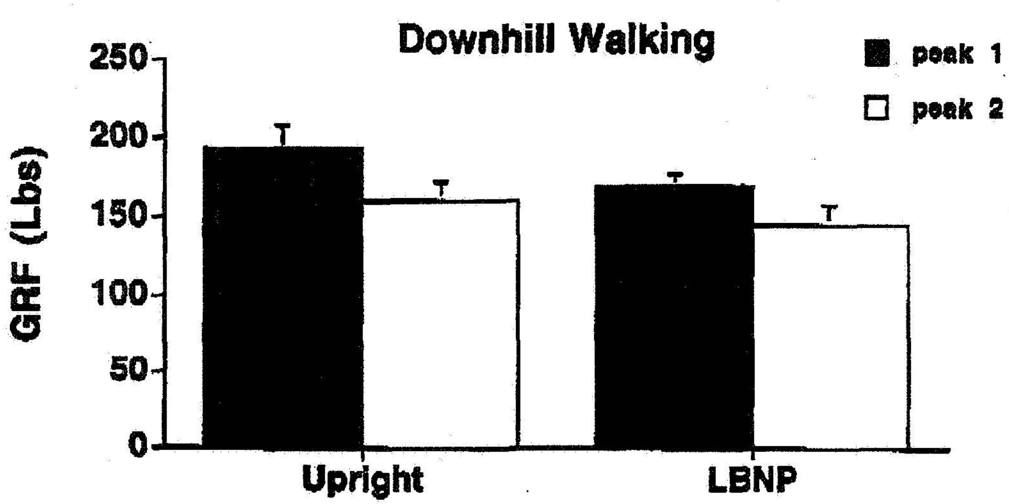
6


HR139 Running Peaks
GRF (Lbs)
0
100
200
300
400
Upright
LBNP
uphill
horizontal
downhill

7







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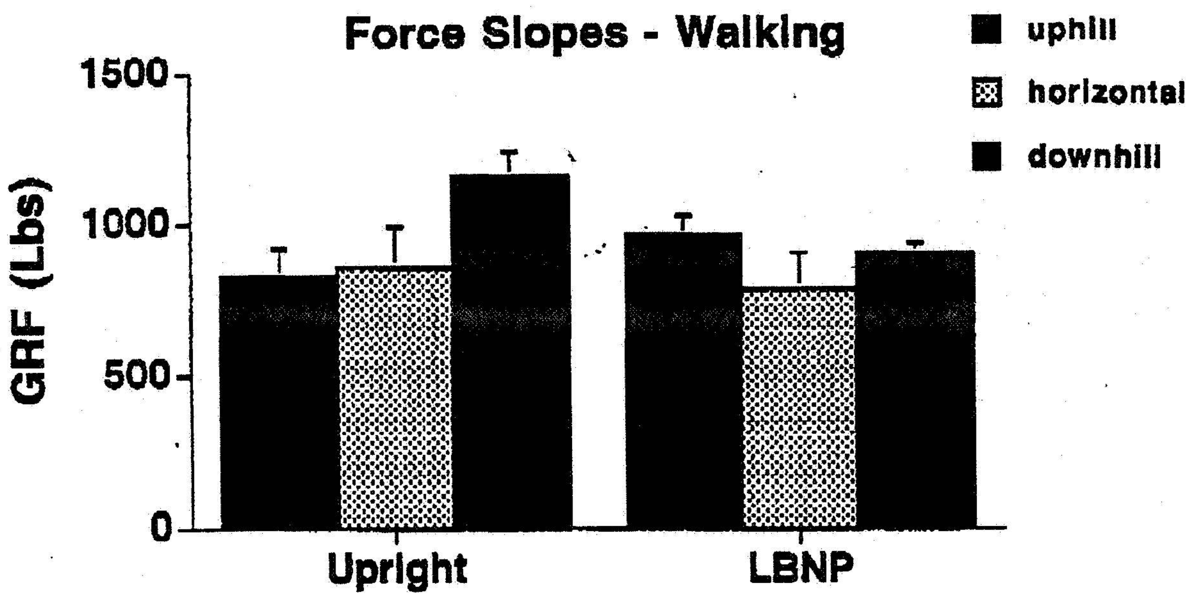
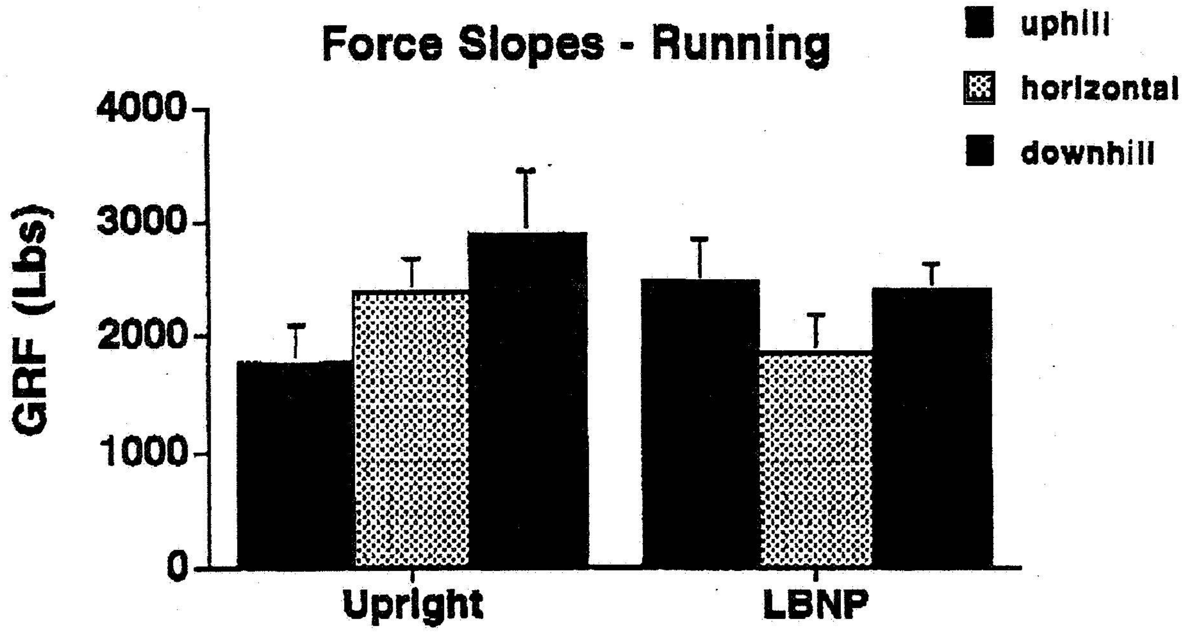

Force Slopes - Walking
uphill
horizontal
downhill
GRF (Lbs)
1500
1000
500
0
Upright
LBNP


Force Slopes - Running
uphill
horizontal
downhill
GRF (Lbs)
4000
3000
2000
1000
0
Upright
LBNP